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Emittance Studies for the TTF FEL Photoinjector

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Abstract

The Free Electron Laser at the TESLA Test Facility (TTF FEL) is based on the principle of the so-called self amplified spontaneous emission, which requires an electron beam with very high phase space density. In order to meet the requirements an rf gun is under test at DESY. In this paper the emittance of the electron beam as function of the charge is investigated by means of PARMELA simulations. The effect of solenoid offset and of beam offsets at the cathode onto the beam emittance is discussed. The emittance growth due to field unbalance in the gun is mentioned and the frequency difference between p-mode and 0-mode as function of the field balance is presented.

1 Introduction

The Free Electron Laser at the TESLA Test Facility (TTF FEL) [1] is based on the principle of the so-called self amplified spontaneous emission, which requires an electron beam with very high phase space density. In the final stage a transverse emittance of 1 p mm.mrad and a longitudinal emittance of 20 mm.keV should be achieved. In order to meet this requirements an rf gun is under test at DESY. Simulations show that the required phase space density can be reached if a laser with fast rise time and a capture cavity with high gradient are available [2] [3] [4]. This paper is devoted to simulations based on parameters that have already been reached at the TTF, i.e, longer laser rise time and a lower accelerating gradient in the capture cavity. In addition some factors may affect the emittance are considered carefully.

This paper is organized as the follows: the emittance of different bunch charge from 0.5 nC to 8 nC along the beam line is calculated in the second section, and then a scaling law for the emittance estimates with different bunch charge is obtained. The emittance and beam position along the beam line with different transverse solenoid offset are presented in the following section. In the fourth section, the emittance of the bunch with an initial transverse offset at the cathode is discussed. The emittance growth due to the unbalanced RF field of the p-mode is mentioned and also the relation between the RF field uniformity of the p-mode vs frequency difference between the p and zero modes is given in the fifth section.

2 Emittance with different bunch charge

The design bunch charge for the FEL operation is 1 nC. However, experiments will be made also with other bunch charges. PARMELA [5] simulations were carried out to find scaling laws for the transverse and longitudinal emittance in the range of 0.5-8 nC bunch charge.

The TTF FEL photoinjector consists of a 1.5 cells RF gun, a focusing solenoid which surrounds the full cell for the compensation of emittance blow up, and the capture cavity which is

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a 9-cell superconducting cavity for the further acceleration and focusing of the bunch, as schematically shown in Figure 1. The bucking coil behind the RF gun is used to compensate the solenoid field on the cathode. Our emittance calculation is up to 355 cm from the cathode, since the emittance is close to the minimum value at this point. Table 1 lists the PARMELA settings.

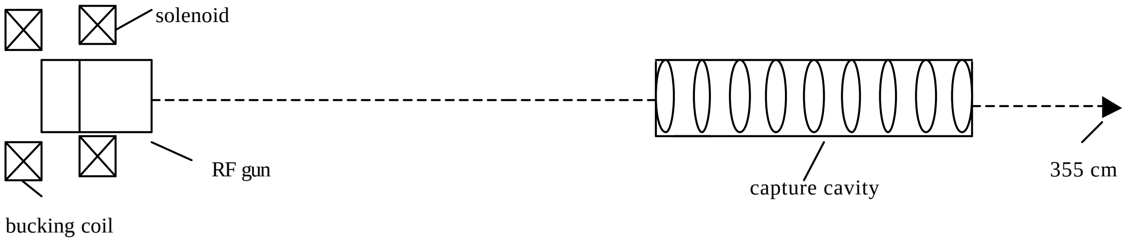
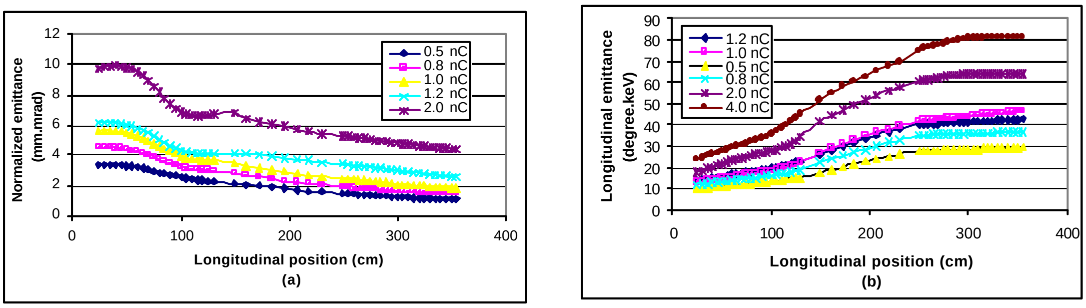


Figure 1: Schematic map of the TTF FEL photoinjector

Table 1: The PARMELA settings with different bunch charges

bunch charge	0.5 – 8 nC
initial bunch radius at the cathode	1 mm – 5 mm
RMS laser pulse length (gaussian)	5 ps
maximum accelerating gradient at the cathode	50 MV/m
average accelerating gradient in the capture cavity	E_0 = 12 MV/m



(a) Normalized transverse emittance

(b) Longitudinal emittance

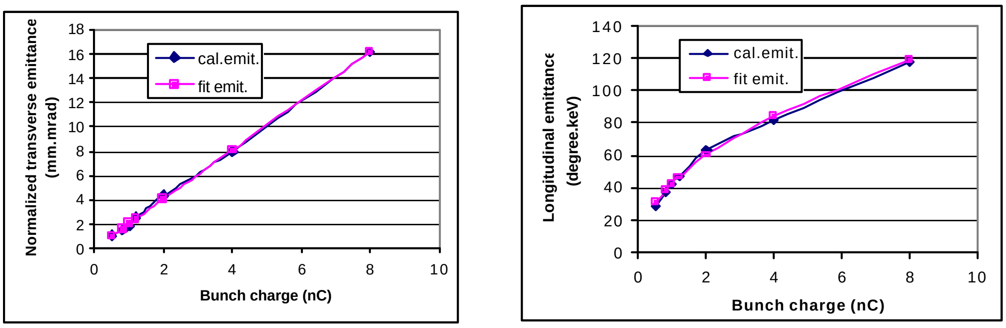
Figure 2: Emittances along the longitudinal position with different bunch charge

Using these settings and then optimizing the phase of the RF gun and the capture cavity, one can obtain the energy at the exit of the RF gun and the capture cavity of, 5.3 MeV and 16.4 MeV, respectively. By optimizing the solenoid field, the transverse and longitudinal emittances along the photoinjector are obtained, as shown in Figures 2(a) and 2(b). With a least-square fit, the scaling laws for the transverse and longitudinal emittance estimate at 355 cm for a longitudinally gaussian laser pulse are given as followings:

$$e_{x,y} = 2.015Q + 0.024\,\text{(mm.mrad)} \quad (1)$$

$$e_z = 27.13Q^{0.493}\text{(mm.keV)}, \quad (2)$$

where the $e_{x,y}$ and e_z mean the normalized transverse emittance and longitudinal emittance, respectively, and Q is the bunch charge in unit of nC. The calculated and fitted emittances (normalized transverse emittance and longitudinal emittance) at 355 cm is shown in Figure 3. It is shown that the normalized transverse emittance is proportional to the bunch charge. And, the longitudinal emittance is proportional to the square root of the bunch charge. Smaller emittance can be reached with a longitudinally more uniform laser pulse.



(a): transverse emittance

(b): longitudinal emittance

Figure 3: The emittance at 355 cm for a laser pulse with longitudinal gaussian distribution

3 Emittance and beam offset along the beam line vs transverse solenoid offset

3.1 Emittance vs transverse solenoid offset

The focusing solenoid in the RF gun is for the compensation of emittance's blow up. The longitudinal magnetic field Bz at a transverse offset from the solenoid axis can be derived as follows. From the equation $\nabla^2 B_z = 0$, one obtains:

$$\frac{\partial B_z}{\partial r} = -r\frac{\partial^2 B_z}{\partial r^2} - r\frac{\partial^2 B_z}{\partial z^2} \tag{3}$$

and thus

$$\left.\frac{\partial B_z}{\partial r}\right|_{r=0} = 0\,. \tag{4}$$

From equation (3) and some algebra, one can have

$$\frac{\partial^2 B_Z}{\partial r^2} \approx -\frac{1}{2}\frac{\partial^2 B_z}{\partial z^2} \tag{5}$$

and due to

$$B_z(r) = B_z(0) + \left.\frac{\partial B_z}{\partial r}\right|_{r=0} \cdot r + \frac{1}{2!}\left.\frac{\partial^2 B_z}{\partial r^2}\right|_{r=0} \cdot r^2 + O(r)\,, \tag{6}$$

where r is the transverse solenoid offset, $O(r)$ is of smaller magnitude in high orders. Substituting equations (4) and (5) into (6), the longitudinal magnetic field at the transverse offset can be expressed as:

$$B_z(r) = B_z(0) - \frac{1}{4}\frac{\partial^2 B_z}{\partial z^2}\bigg|_{r=0} \cdot r^2 \tag{7}$$

The second order term component in equation (7) is of small magnitude, and can be neglected. Especially at the cathode $\frac{\partial^2 B_z}{\partial z^2} \approx 0$, since Bz is almost linear in z due to the solenoid–bucking coil arrangement. Therefore, from the qualitative analysis the longitudinal magnetic field at the transverse offset is equal to the longitudinal magnetic field at a longitudinal position on axis. Applying the POSSION code, the ratio of Bz(r) to Bz(0) is near 1.0, which agrees with the analytical result, as shown in Figure 4.

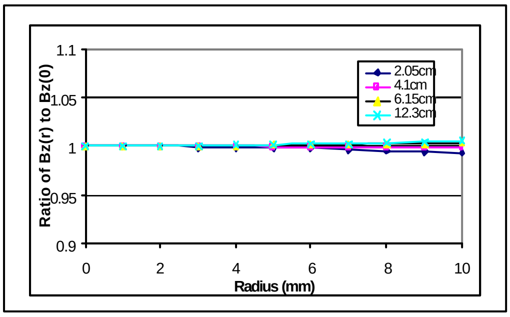


Figure 4: Ratio of Bz(r) to Bz(0) vs radius

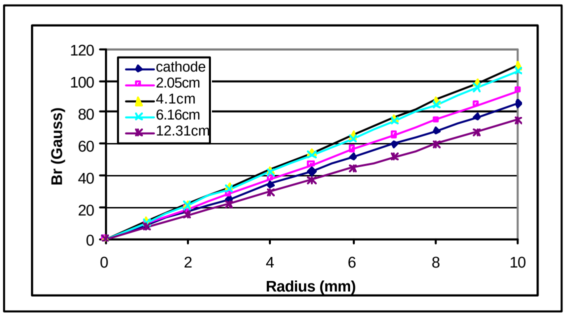
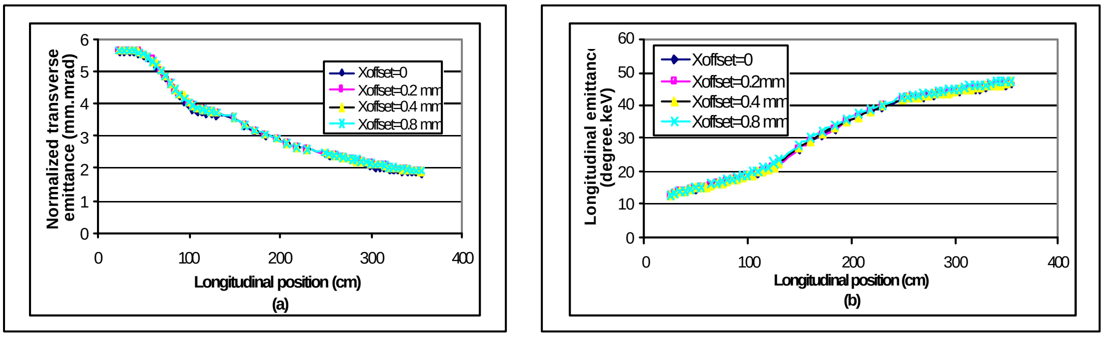


Figure 5: Br vs r at different longitudinal position



(a) Normalized transverse emittance

(b) Longitudinal emittance

Figure 6: Emittances along the longitudinal position with different transverse solenoid offset

In a similar way, the transverse magnetic field with a transverse offset can be obtained from $\nabla \cdot B = 0$ as:

$$B_r(r) = B_r(0) - \frac{1}{2}\frac{\partial B_z}{\partial z}\bigg|_{r=0} \cdot r \tag{8}$$

Since $B_r(0) = 0$, one can have

$$B_r(r) \propto r\,, \tag{9}$$

which also agrees with the simulation data, as shown in Figure 5. Applying the Liouville theorem, the phase space should be kept constant in the linear field. Thus, in the view of the qualitative analysis, the emittance is not changed if the solenoid has a transverse offset.

It is shown in the PARMELA simulations that both the transverse and longitudinal emittances with different transverse solenoid offsets is the same as that of no solenoid offset, as shown in Figures 6(a) and (b), respectively. The transverse wakefield effects on the emittance dilution have been neglected due to the low RF frequency of the TTF cavity and hence the low wakefield.

3.2 Transverse beam offset along the beam line vs transverse solenoid offset

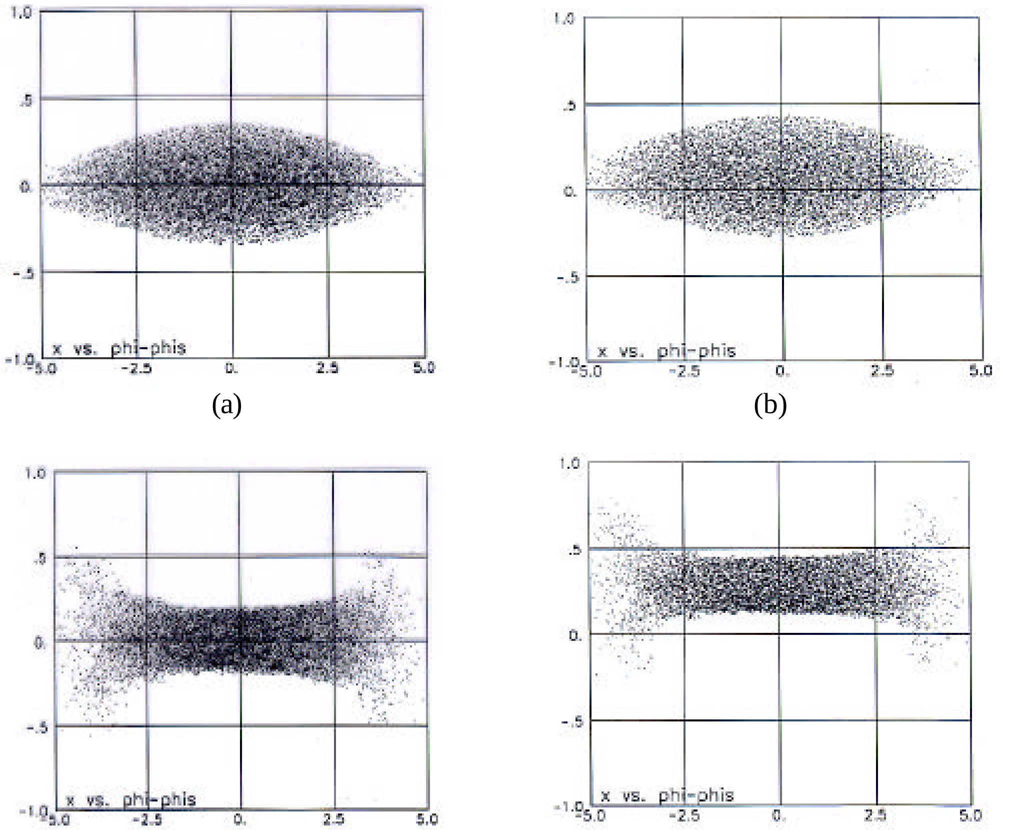
Since the transverse magnetic field at different transverse offset is proportional to the transverse offset, the transverse force which affects the bunch is linear with the transverse offset. The transverse force will result in a transverse shift of the bunch.

PARMELA simulation results with and without transverse solenoid offset at the exit of the RF gun are shown, in Figures 7(a) and (b), and at 355 cm in Figures 7(c) and (d). It is understood that the larger the transverse solenoid offset, the more the transverse shift of the bunch. Table 2 shows the beam transverse position vs transverse solenoid offset. It is shown that the beam transverse offset at 355 cm is amplified from the exit of the RF gun. Further, it is seen that the bunch shift amplification mainly comes from the drift between the RF gun exit and the beginning of the capture cavity.

In the solenoid field region, due to the $B_r(r) \propto r$, there exists the transverse momentum p_r, which will result in a small angle q,

$$q = \frac{p_r}{p_z}\,, \tag{10}$$

where p_z is the longitudinal momentum. In the drift beam line between the RF gun exit and the beginning of the capture cavity, the solenoid field gradually decreases down to zero, but the smalle angle still exists in the rest of the drift where the solenoid field is zero. If the angle is q and the length of rest drift is l_0, the transverse beam shift $\propto l_0 \cdot q$. Therefore, only if the angle is constant in the rest drift, the transverse bunch shift is larger at a longitudinal position far from the cathode.



(a) (b)

(c) (d)

(a): Gun exit, horiz. solenoid offset=0 mm (b): Gun exit, horiz. solenoid offset =0.8 mm
(c): 355 cm, horiz. solenoid offset =0 mm (d): 355 cm, horiz. solenoid offset = 0.8 mm

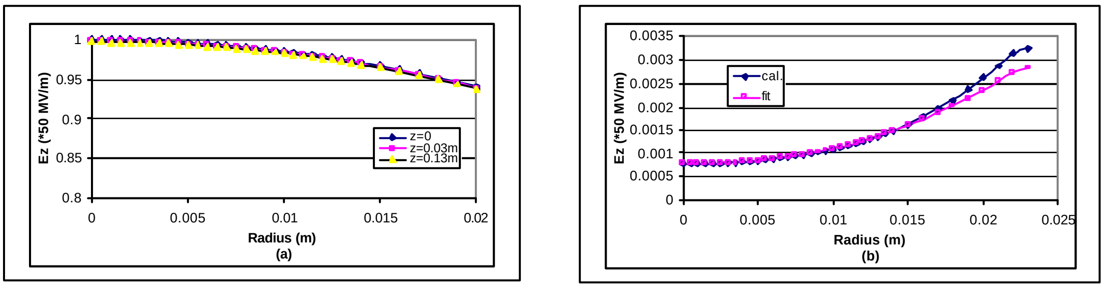
Figure 7: Horizontal beam profiles at different locations with and without trans. solenoid offset

Table 2 Transverse beam offset vs transverse solenoid offset

	Gun exit (25 cm)		Begin of capture cavity (130 cm)		end of capture cavity (249.5 cm)		355 cm	
Solenoid Horiz. Offset (mm)	Horiz. beam offset (mm)	Verti. beam offset (mm)	Horiz. beam offset (mm)	Verti. beam offset (mm)	Horiz. beam offset (mm)	Verti. beam offset (mm)	Horiz. beam offset (mm)	Verti. beam offset (mm)
0.2	0.2	0	0.7	0.6	0.6	0.6	0.7	0.7
0.4	0.4	0	1.3	1.3	1.3	1.3	1.3	1.8
0.6	0.6	0	2.0	2.0	2.0	2.0	2.0	2.5
0.8	0.8	0	2.8	2.4	2.6	2.6	3.0	3.0

4 Emittance vs transverse bunch offset at the cathode

Ideally, the cathode is in the center of EM-field axis of the gun cavity, and the laser should touch the center of the cathode. Then the electrons would be emitted symmetrically from the cathode near the axis. The RF field acts on the electrons symmetrically, if the RF field is symmetric.



(a) Ez at the cathode, half cell and full cell

(b) Ez at the iris

Figure 8: Longitudinal accelerating electric field in the RF gun

If the bunch has a transverse offset from the axis at the cathode, what about its emittance growth? This question can be studied analytically or by simulations with MAFIA TS3 [6], which is a 3-dimensional particle in cell module (PIC) and computes the time integration of electromagnetic fields selfconsistently with the time integration of the equations of motions of charged particles that move under the influence of those fields.

The RF fields in the RF gun are calculated by the MAFIA Eigen Solver [6]. It is shown that the longitudinal electric field of the accelerating mode at transverse offsets below 10 mm is nearly constant except in the iris region, as shown in Figures 8(a) and (b), In the iris region, the longitudinal electric field is almost proportional to the square of the transverse offset (fitting line $\propto r^{2.2}$ in Figure 8(b)), but the amplitude is very low, only 0.8% of the longitudinal electric field at the cathode. Thus, the bunch is not accelerated in the iris region, and its emittance is not diluted. The transverse electric field $E_r(r)$ is proportional to the transverse radius below 10 mm in the RF gun. According to the Liouville theorem, the phase space is not changed under such linear field. Therefore, by analyzing the RF field in the RF gun, the emittance is not changed when the bunch has a transverse offset below 10 mm.

According to the MAFIA TS3 simulations, the transverse emittance at the exit of the RF-gun is almost not changed, i.e., the emittance growth is only below 5.0%, when the initial bunch transverse offset at the cathode is below 10 mm. When the initial bunch transverse offset is larger than 20 mm, the bunch can not be monitored at the exit of the RF gun in the simulations. In this case, the bunch may hit the iris of the RF gun due to the limited iris radius of 25 mm.

5 RF field uniformity of the RF gun and its correlated emittance

In the RF gun, the bunch is accelerated by the longitudinal electric field of the p -mode. In order to minimize the emittance growth in the RF gun, the ratio of the p -mode field in the half cell (E_h) to the full cell (E_f) should be kept around 1.0 at the resonance frequency [1]. If the field amplitude in the half cell is different from the one in the full cell, the emittance might blow up due to the discontinuous RF field. According to the simulations [7], E_h / E_f =0.75 will cause about

100% emittance growth, while E_h / E_f =1.25 will cause 70% emittance growth and also increase b function from 20 m to 90 m. All parameters settings in the above simulations with different E_h / E_f are the same. In the case of $E_h / E_f \neq 1.0$, the emittance growth may be somewhat decreased if the parameters, such as solenoid field and gun phase are optimized.

In the cold test, the field ratio can be made near 1.0, i.e., the field of the p-mode in the half cell and full cell is balanced. However, under load some parameters of the RF gun might be changed somewhat, and the field balance may be broken. The field balance can not be directly monitored during operation, however, it is clear that the field ratio E_h / E_f is related to frequency difference between the p and zero modes, Δf_{0p}, which can be directly measured during operation. Thus, in order to monitor the field balance it is useful to calculate the relation between Δf_{0p} and the field ratio E_h / E_f.

In the MAFIA Eigen simulations, one can put dummy ring-type tuners in the half cell and full cell, respectively, and the dummy tuners will disturb the frequencies and fields of the modes, as shown in Figure 9. By changing the height of the tuners from 1 mm to 4 mm, the corresponding frequencies and fields of the modes are calculated. The field uniformity can be defined as following:

$$uf = \frac{|E_h| - |E_f|}{|E_h| + |E_f|} \tag{9}$$

The curve of the field uniformity uf with Δf_{0p} is shown in Figure 10.

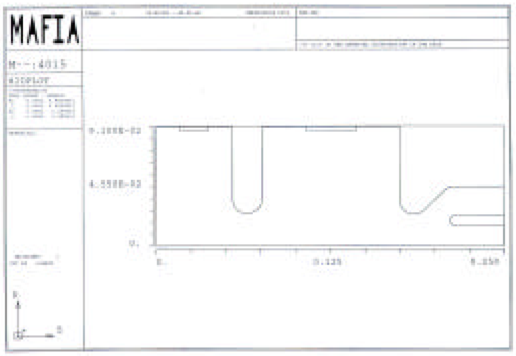


Figure 9: Drawing of the gun with dummy tuners

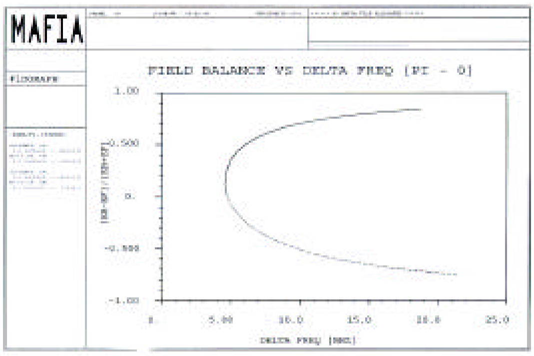


Figure 10: Field uniformity of the gun vs Δf_{0p}

6 Summary

The emittance studies for the TTF FEL photoinjector are summarized as follows:

- The normalized transverse emittance changes with varying bunch charge at a gaussian rms laser pulse 5 ps by a scaling law, which is proportional to the bunch charge. The longitudinal emittance is proportional to the square root of the bunch charge.

- The transverse solenoid offset has a small contribution to the transverse and longitudinal emittances, but the bunch will have a transverse non-negligible shift along the beam line.

- By the field analysis and MAFIA TS3 simulations, the emittance of a bunch which has an initial transverse offset (smaller than 10 mm) at the cathode does not blow up along the beam line.

- If the p -mode field in the half cell and in the full cell is not balanced, the emittance will blow up. The relation between the accelerating field uniformity vs the frequency difference between the p and the zero modes is presented.

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